

Hydrogen Maser Frequency Standard: Receiver Configuration and Stability Requirements

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The final receiver configuration and current status of the Jet Propulsion Laboratory hydrogen maser is discussed along with the phase noise and stability requirements for the various receiver modules.

I. Introduction

This is one of a continuing series of articles discussing the development of a hydrogen maser for use as a station standard in the DSN. The major objectives of this project are to develop a frequency standard that can: (1) guarantee a long-term frequency stability of at least 6×10^{-15} , (2) be reproduced on a semi-production basis from minimal documentation by non research and development (R&D) personnel, (3) be easily operated by site personnel and calibrated at station depots, and (4) operate on a one-to two-year major service interval.

II. Mechanical Configuration and Operation

The JPL hydrogen maser consists of two assemblies, the physics unit and the receiver unit, which are connected by cables. The physics unit must reside in an area free of magnetic interference, while the receiver, which is housed in a standard DSIF rack, is normally placed in the control

room. A 120-Vac 15-A line powers the entire system which can be supplied through a 2-kW uninterruptible power supply (UPS) if uninterrupted operation is desired.

The receiver-control rack uses a modular approach to facilitate maintenance and future upgrading. The rack houses three power supplies and a synthesizer with the control section packaged in two cages of Nim-Bin modules and the receiver-synthesizer occupying three cages of the new DSIF standard radio-frequency (RF) module type B. All the receiver modules except the front end, which is mounted on the RF oven plate in the physics unit, are located in the rack and are easily replaceable. Each of the 18 modules is preadjusted during assembly and the entire receiver can be calibrated in one step by the operator without auxiliary equipment.

A number of self-testing features are built into the maser for ease of post-assembly calibration and maintenance in the field. The receiver contains a test oscillator

that synthesizes the maser frequency from an external 5-MHz reference and is used any time the maser signal is absent. Also included is an audio oscillator that measures the Zeeman frequency of the cavity and a multiple function digital panel meter that indicates various operating parameters, including the maser output power.

III. Physics Unit

A long-standing problem of hydrogen masers has been hard starting and low output power (-95 dBmW). A unique bulb coating (Ref. 1) has improved this situation by raising the output by 10 dB, thereby directly improving short-term stability due to a better signal-to-noise ratio. An added advantage is that full power can be obtained after about 30 min of pumping down the vacuum. Another difficulty with previous masers is the perturbation of the maser's phase by the vacuum pump at high flux levels. The traditional solution has been to lower the maser's output, but attention is presently focused on modifying the pump elements to withstand higher flux levels without disturbing the maser's output (Refs. 2, 3). In addition, mechanical reliability is being stressed and a special container has been fabricated for shipping the relatively delicate physics unit over common carriers.

The problem of maintaining cavity tuning over long periods of time has been greatly simplified. A method of automatic tuning (Refs. 4, 5, 6, 7) operates two masers in a master-slave mode whereby the first maser varies its flux to detect a tuning error, while the second maser tunes its varactor-controlled cavity to match the averaged frequency of the first. The difference in frequency of the two masers is generated by the zero crossing detector module which compares each of the 100-MHz outputs from the masers and sends the error information on a 0.01-Hz carrier to the auto-tuner control module which, in turn, applies the required cavity correction.

IV. Receiver

Some hydrogen masers fall short of expectations in the area of long-term stability simply because so much effort is expended on the complex physics unit that receiver performance is degraded through lack of development. One of the major challenges of the JPL hydrogen maser has been to design a receiver that can translate the maser's long-term stability directly into usable output frequencies. To achieve a "useable" output frequency distribution system, every standard frequency is provided with multiple outputs at a high power level and high isolation. This is necessary since the use of supplementary amplifiers, mul-

tipliers, and dividers can degrade performance by over two orders of magnitude. Table 1 lists the outputs that are available at the interface panel located on the bottom of the receiver rack. Also each of these frequencies (except 1400 MHz) has one additional output that is available on the front of the receiver.

The final configuration of the receiver-synthesizer (shown in the simplified block diagram of Fig. 1) is a triple conversion phase-lock receiver with a divider chain providing the standard distribution frequencies. Although the receiver appears rather conventional, a great deal of effort was expended in researching a configuration that could meet the stability and phase noise requirements of the maser with present state-of-the-art techniques. For example, the prototype masers that are currently operating at DSS 14 use a substantially more complex quadruple conversion receiver simply because the earlier model synthesizer lacks the resolution required to set the output frequencies within the required tolerances. The new receiver employs a synthesizer (Refs. 8, 9) with a resolution of $1 \mu\text{Hz}$ which allows the output to be accurately set to within 7 parts in 10^{16} . Other areas of development include front end isolators with highly stable input VSWRs and magnetic shielding to prevent cavity detuning, a 0.02% bandwidth crystal filter in the first intermediate frequency (IF) that can meet the required phase stability without an oven, a sampling phase locked loop $\times 14$ multiplier (Refs. 10, 11) that achieves a 10-dB reduction in phase noise over conventional circuits, a 100-MHz VCO (Ref. 12) with low phase noise that requires retuning only once a year, and finally a divider-distribution amplifier (Refs. 13, 14, 15) chain with extremely low phase noise, 100-dB isolation between outputs, and meeting stringent stability requirements without the use of ovens.

V. Stability and Phase Noise Requirements

In view of the performance of the present hydrogen masers a long-term stability requirement of 10^{-15} was chosen for the overall receiver when operating in a control room environment. Since the stability requirements are severe it is important that the test conditions simulate the actual operational environment in order to avoid overly restrictive specifications. Investigation in this area revealed that most of the phase drift in the receiver is caused by temperature variations in the plenum air that cools the rack. A one-week monitor of the plenum air at DSS 14 showed a 2°C variation in temperature with a maximum short-term perturbation of 0.5°C lasting about 400 s. These data became the basis for the test conditions stated in *Footnote a* of Table 2. For the receiver modules

listed in Table 2 the phase drift rates were assumed to be cumulative, i.e., none of the phase drifts canceled each other. All the modules within the loop receive phase correction equal to the ratio of the maser frequency to the voltage-controlled oscillator (VCO) frequency, excepting the VCO and the 100-MHz distribution amplifier which theoretically receive almost infinite correction. In practice however, these two modules require a minimum amount of stability to prevent adverse effects on acquisition and hold-in performance of the loop. The fact that fractional frequency stability depends only upon phase drift *rate* (radians/second) implies that a module may have a very large phase drift provided it is slow in responding. This is harmless to the receiver loop but can have a disruptive effect on systems that use several of the hydrogen maser outputs simultaneously and are dependent on the relative phase between the outputs remaining constant. Therefore, all the outputs of the maser have a requirement holding the phase to within 5° over a 0 to 50°C temperature range.

Since most of the modules exhibit a $1/f$ phase noise spectral characteristic below 1 kHz, a noise reading at 10 Hz has been chosen as the standard measure of performance within the receiver loop bandwidth of 100 Hz. At an output of -85 dBmW the power spectral density of phase for the hydrogen maser at 10 Hz is about $-109\text{ dB rad}^2/\text{Hz}$ (Ref. 16). Ten percent of this noise was chosen as the maximum allowable contribution by the receiver loop and is the basis for the noise requirements in Table 2. However, as the maser noise progresses through the divider chain outside the loop, it is successively divided until it is reduced to -169 dB at the 100-kHz output. Even the best amplifiers (Ref. 17) as yet do not have noise levels below -150 dB and substantial problems exist in

measuring phase noise performance below -140 dB due to the difficulty in eliminating amplitude modulation (AM) to phase modulation (PM) conversion in the test configurations. Since phase noise is additive rather than multiplicative, the desirability of achieving low phase noise while retaining high isolation in the distribution amplifiers has brought about an important compromise, for high isolation requires many stages, yet each additional stage will increase the phase noise by 6 dB (assuming identical stages).

One final consideration in the design of the hydrogen maser has been the stability of the coaxial cable (Refs. 18, 19) that interconnects the various components. To achieve sufficient stability, short lengths of semirigid, solid dielectric cable are used in the receiver rack and a 1.5-cm ($\frac{1}{2}\text{ in.}$) corrugated foam dielectric line is used for the microwave cables from the physics unit. Preserving the stability of a reference frequency over a long distance cannot be done with any presently available cable; however, currently under development is a pneumatic controlled form of active phase compensation wherein the electrical length of the cable is varied by adjusting the air pressure within the line.

VI. Conclusion

Although the hydrogen maser has demonstrated the capability of generating highly stable reference frequencies, new techniques will be needed to distribute this stability to the user destinations. This will require advanced development in the areas of station distribution amplifier banks, control room cabling, and intersite microwave links.

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Table 1. Frequencies available from the hydrogen maser

Frequency	1400	100	20	10	5	1	0.1	MHz
Number of outputs available	1	3	2	3	3	3	2	—
Level	+13	+13	+13	+13	+13	+13	+5V ^a	dBmW
Isolation	75	100	100	100	100	100	60	dB
^a TTL level								

Table 2. Hydrogen maser receiver modules: stability and noise requirements

Module output	Stability ^a	Correction ^b	Phase ^c noise, dB	Correction, ^d dB	Temperature coefficient ^e of phase, deg/°C
Front end	1×10^{-14}	1	−124	23	—
X14 multiplier	1×10^{-16}	1.02	−124	23	—
First IF	7×10^{-15}	69.6	−124	23	—
Second IF	3.5×10^{-13}	3501	−124	23	—
Phase detector	3.5×10^{-13}	3501	−124	23	—
VCO	2×10^{-12}	>20,000	−104	>43	—
100-MHz DA ^f	2×10^{-12}	>20,000	−104	>43	0.1
20-MHz DA & ÷ 5	7×10^{-15}	71	−124	23	0.1
10-MHz DA & ÷ 10	1×10^{-16}	1	−139	0	0.1
5-MHz DA & ÷ 2	1×10^{-16}	1	−145	0	0.1
1-MHz DA & ÷ 10	1×10^{-16}	1	−145	0	0.1
0.1 MHz DA & ÷ 100	1×10^{-16}	1	−145	0	0.1
Synthesizer	3.5×10^{-13}	3501	−124	23	—

^aThe fractional frequency deviation $\Delta f/f$, for averaging times between 100 and 10,000 s, resulting from a step change of 5°C in the ambient temperature of a module within the range of 0 to 50°C.

^bThe factor of improvement applied to a module's stability when the module is operating in the receiver.

^cThe one-sided power spectral density of phase noise (in rad²/Hz) measured at 10 Hz away from the center frequency.

^dThe factor of improvement in a module's phase noise when the module is operating in the receiver.

^eOver a temperature range of 0 to 50°C.

^fDA = distribution amplifier

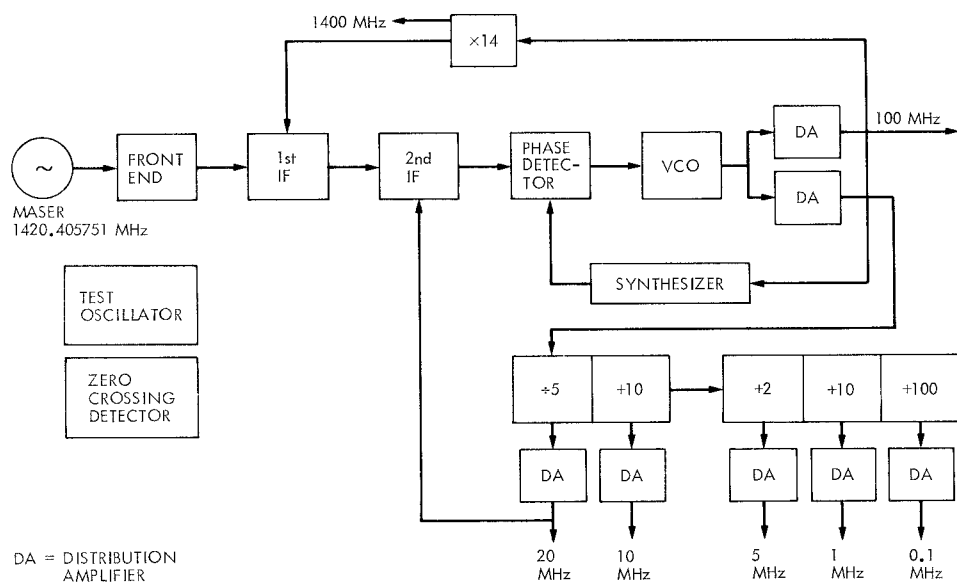


Fig. 1. Hydrogen maser receiver block diagram